

APPENDIX A: Methodologies Used to Determine Causes

Material and Structural Analysis

Fracture of the 18,000-gallon propane tank likely initiated at an internal pressure in excess of 250 psi. This conclusion is based on observations by eyewitnesses that the relief valves, which were set to open at 250 psi, were discharging before the tank failed, and that the tank had been subjected to a hydrostatic test pressure of 375 psi after fabrication. Although the failure pressure was probably greater than 250 psi, it is impossible to establish an exact failure pressure without knowing the complete pressure-temperature history for the tank. It is possible, however, to identify an upper bound failure pressure and estimate the actual failure pressure using fundamentals of science and engineering.

Design rules in the American Society of Mechanical Engineers Boiler and Pressure Vessel Code provide a substantial margin of safety against overpressurization. Under certain operating temperatures and conditions, the factor of safety can be as high as four. Based on this value, the pressure corresponding to failure could have been as high as 1,000 psi, provided the temperature of the shell and heads remained relatively low (less than about 650 F). However, because of the fire and the deleterious effect heat has on the properties of carbon steel, it is likely that the tank failed at a pressure below 1,000 psi.

At about 650 F, the tensile strength of carbon steel begins to decrease as the temperature increases. When carbon steel begins to glow red at about 1,000 to 1,100 F, its tensile strength is only about 60 percent of its room-temperature strength. Any reduction in tensile strength resulting from high-temperature exposure produces a corresponding reduction in the failure pressure. With the maximum flame temperature of propane in air approximately 3,595 F and the presence of fire underneath the tank, it is likely that the properties of the steel in the vicinity of the flames were affected by the intense heat of the fire.

As propane leaked from the tank and fueled the fire, the flames heated the tank wall above the liquid level inside the tank, causing changes in the properties of the steel. At some point when the overheated steel lost sufficient strength and could no longer resist the pressure-induced forces, fracture initiated. Because there was no liquid propane near the top of the tank to absorb the heat, fracture probably initiated at a point above the liquid level where the metal was the hottest. However, fracture initiation at a point below the liquid level is also possible because of film boiling and the formation of a vapor blanket at the steel-liquid interface inside the tank resulting from direct flame impingement.

Results of metallurgical studies conducted by NASA on selected pieces of steel cut from the tank are provided in Appendix B. These results provide evidence that the tank failed by overpressurization in a ductile, not brittle, manner. Steel that exhibits ductile failure experiences significant stretching before separation occurs. In addition, there was no evidence of pre-existing cracks or defects in the steel that could have caused the tank to fracture prematurely or

that the strength of the steel was less than specified. Based on NASA findings, the tank performed its intended function as a physical barrier to the pressurized propane that it contained.

Failure Modes and Effects Analysis

Rupture of the tank as a result of overpressurization is consistent with a BLEVE. Fragments produced by the explosion produced significant property damage and was the cause of the deaths to emergency response personnel.

Based on visual examination of the shapes of the piping and metal debris discovered at the scene following the incident, it is unlikely that the carbon steel pipes and fittings used to construct the piping system failed by overpressurization. Observed piping fractures probably occurred for one or more of the following reasons:

- the all-terrain vehicle struck the ¾-inch nominal size liquid propane piping, causing the pipe connection at the bushings in shut-off valve A20 to fail;
- pieces of the tank impacted the piping following the explosion; or
- the piping separated from the tank and broke as a result of the explosion.

Shut-off valves A19 and A20, used on the liquid propane piping lines (see Figure 6), were rated for 400-psi service at temperatures up to 150°F. However, pressure required to cause failure is usually at least twice the rated operating pressure. Shut-off valves A19 and A20 did not fail by overpressurization. Observed damage was probably caused by impact following the explosion.

Damage to the concrete saddles that served as foundations for the tank was probably caused by forces produced by the explosion, heat generated by the fire, or impact by pieces of the tank. It is unlikely that the concrete had any measurable effect on the failure mode of the tank, but the saddles may have influenced the trajectory of some of the pieces.

Incident Reconstruction Analysis

Testing of piping components retrieved from the Herrig Brothers Farm following the incident was conducted by NASA at the Kennedy Space Center in Florida to reconstruct the incident scenario. This testing was conducted to establish the flow performance and behavioral characteristics of excess flow valve FV3 (see Figure 6), which was part of the 18,000-gallon propane storage and handling system piping impacted by the ATV.

Flow testing was performed using two configurations. One configuration was intended to simulate installation in accordance with manufacturer's recommendations. In this test, excess flow valve FV3 closed as soon as simulated fracture of the attached piping occurred, thus demonstrating that the valve was capable of performing its intended function. In the second configuration, excess flow valve FV3 was provided with downstream piping of the same size as the actual installation. In this test, the valve did not close as soon as the simulated fracture of the attached piping occurred. This result demonstrated that the actual piping arrangement produced

flow conditions sufficient to keep excess flow valve FV3 from closing. Details of the NASA flow testing program are provided in Appendix B.